SOLIDIFICATION CRACKING STUDIES ON STEELS

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ABSTRACT

Three steels namely, Cr-Mo steel equivalent to 4130, modified 4340 steel containing higher silicon and high nickel whose strength is equivalent to maraging steel 250 and a maraging steel have been studied for their solidification cracking behaviour during continuous current gas tungsten arc welding employing varestraint test system. The Cr-Mo steel was also subjected to pulse mode of gas tungsten arc welding to understand the influence of current pulsing on solidification cracking behaviour. Cr-Mo steel exhibited least solidification cracking tendency while modified 4340 steel (silicon steel) showed marginally higher cracking tendency than the maraging steel. Cr-Mo steel exhibited a greater tendency to cracking in pulsed mode of welding than in conventional welding. The observed cracking tendency of cracking in pulsed mode of welding is explained on the basis of possible differences in the weld thermal history between conventional welds and pulsed welds.

Keywords : *Solidification cracking, Cr-Mo steel, Maraging steel, Ultra high strength steel, Varestraint test, Houldcroft test, Tekken test*

INTRODUCTION

High strength and ultra high strength steels are widely used for defence and aerospace applications to take advantage of their strength/weight ratio [1]. Such steels can be prone to solidification cracking during welding. The causes for solidification cracking in stainless steels have been widely studied [2, 3]. However, such studies are scarce in the high and ultra high strength steels. Studies on electron beam welding of HY-100 high strength steel and AISI 4340, ultra-high strength steel revealed that these steels are prone to solidification cracking [4].

The high level of carbon in this steel, which caused the steel to solidify as austenite promoted solidification cracking. Liquation cracking studies on HY-80 steel showed that the steel is prone to liquation cracking due to formation of low melting point eutectic reaction between Cr, Ni and Mn [5]. The solution to mitigate this problem in HY-80 is proposed to be by a modification in the composition by reducing C, N and Cr. AISI 4130 and 4340 are heat treatable steels, which are extensively employed in aerospace applications [1]. Micro-cracking and micro-porosity studies in ultra high strength AISI 4340 steel welds showed that these steels are prone to micro-cracking due to micro-segregation of sulfur and phosphorous in the inter-dendritic regions [6]. The same study has shown that the solidification cracking can be controlled by tailoring the composition, as different elements have differing segregation tendencies to the interdendrtitic regions. The high carbon high strength steel which exhibits numerous welding problems [1] has been replaced by the more weldable maraging steel [7]. At present, there is a move to replace this costly steel by low alloy ultrahigh strength steels, based on internal studies [8] and the studies by Garrison [9] because of the advantages of improved toughness by the increased additions of Ni and Si.

Keeping in view the wide usage of AISI 4130 (Cr-Mo steel) in aerospace industry and the resurgence of efforts to replace the maraging steels with low alloy ultra high strength steels (Silicon steel). Hot cracking studies are taken up on these three classes of steels for comparative evaluation. Gas tungsten arc welding is chosen as the welding process. To understand the influence of pulse current welding, the steel AISI4130 (Cr-Mo steel) is evaluated for its hot cracking tendency in the pulse and conventional continuous current techniques. Self-restraint tests namely, Houldcroft [10] and Tekken 'Y' groove tests [11-13] as well as Varestraint test, an augmented strain test [14] are selected for hot cracking studies.

EXPERIMENTAL

The parent metals selected for the studies are a low alloy high strength steel equivalent to AISI 4130 (Cr-Mo steel) class, a low alloy ultra-high strength steel, a modified Garsion [9] steel with higher proportion of Ni and Si similar to 18 Ni maraging steel and 300 M respectively. The compositions of the parent materials are given in Table I. In Tekken 'Y' groove tests for the ultrahigh strength quenched & tempered steels, two types of fillers are employed. They are, (i) filler conforming to base composition and (ii) maraging filler. The compositions of the fillers are presented in Table II.

Table I : Chemical Composition of Parent Metals

Alloy	Composition (Wt. %)											
	C	Si	Mn	Cr	Ni	Mo	Co	Al	Ti	Zr	S (ppm)	P (ppm)
Cr-Mo Steel (AISI 4130)	0.3	0.65	0.85	0.9	—	0.25	0.01	—	—	0.01	100	105
Ultra High Strength Steel (Si-Steel)	0.42	2.5	0.32	0.87	3.0	0.25	—	—	—	—	30	70
18 Ni Maraging Steel	0.03	0.1	—	0.25		5.0	7	0.15	0.5	—	100	100

Table II : Chemical Composition of filler metals in TEKKEN test

Alloy	C	Si	Mn	Cr	Ni	Mo	Al
Base Filler (Si-steel)	0.42	2.5	0.32	0.87	3.0	0.25	—
Maraging Filler (W_2)	0.015	0.1	—	—	1.8	2.6	0.5

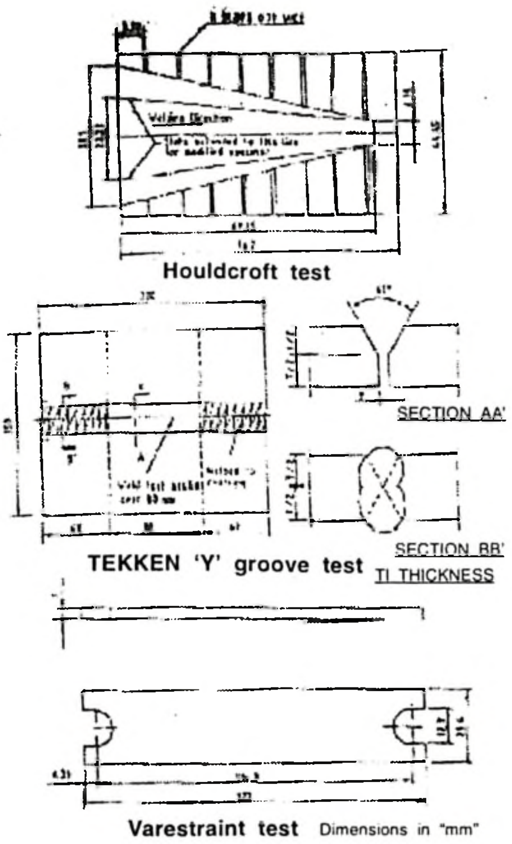

Fig. 1 : Configuration of test specimens

Three types of tests namely Houldcroft, Tekken 'Y' groove and Varestraint tests are performed. In Tekken 'Y' groove, the modified groove namely, straight 'Y' is adopted. The configurations of the test specimens employed are given in Fig. 1.

In Houldcroft and Varestraint testing of ultrahigh strength quenched and tempered steel and maraging steel, the autogenous gas tungsten arc (GTA) welding process parameters were selected such that at least 75% of thickness melted. For varestraint testing of chrome-moly steel both continuous current (CC) GTA and current (PC) welding GTA were selected. The weld parameters are presented in Table III.

In Varestraint test maximum crack length, total crack length and number of cracks were measured. In Houldcroft test the visually observed crack length formed the basis of assessment. In Tekken 'Y' groove the test portion is cut into six sections and each section was observed for the presence of cracks at magnifications of 20X and 100X. The Varestraint specimens were examined at a magnification of 50X.

RESULTS AND DISCUSSION

In Table IV the Varestraint data on Cr-Mo steel are presented. Typical micrographs showing the cracks are presented in Fig. 2. From the data presented in the Table IV, it is observed that upto about 0.945% strain no cracks are observed and at strains of 1.89% and above cracks are observed. The number of cracks and maximum crack length increase which increase in the strain. PC weld exhibited more cracking tendency at a lower strain of 1.89% than at 3.75% strain. In respect of number of cracks PC welds exhibited more cracking than CC weids.

Table III :
Gas tungsten arc welding parameters used in this study

(i) Continuous Current	
Travel Speed	25 cm/min
Current	80 A
Arc Voltage	18-20 V
Argon flow rate	8 CF/minute
(ii) Pulse Current	
Travel Speed	12.5 cm/min
Peak current	130 A
Base current	25 A
Arc Voltage	10-12 V
Pulse on time	20%

The micrographs in Fig. 2 do show that the cracks are not extensive and they are at a micro level and the same is supplemented by the very

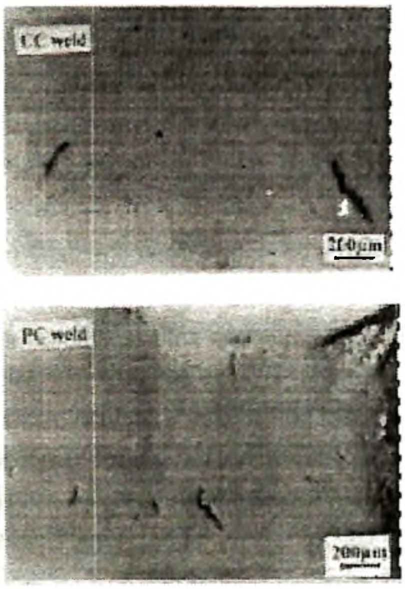

Fig. 2 : Micrographs of Varestraint test samples (Cr-Mo-steel) at strain of 3.75%

low value of maximum crack length as well as total crack length. Only microcracks were observed in the weld region. The higher cracking tendency in PC welding might be attributed to more severe cooling in PC. This observation is consistent with similar observations in inconel 625 and 3042 SS [15].

In Fig. 3 Tekken test micrographs are presented. It is observed that usage of filler in unbaked condition results in cracking and baking eliminates cracking. Maraging filler welds are free from cracks even in unbaked condition. This observation suggests that the cracking observed here be probably related to cold cracking although Tekken test is recommended for cold as well as hot cracking assessment. In Houldcroft test the cracks are confined to un-slotted region only (Fig. 4) suggesting 'Si' steel is not prone to hot cracking under the constraints in Houldcroft test.

Varestraint test data on silicon steel and maraging steel are presented in Table V. Typical micrographs pertaining to these are presented in Fig. 5. Silicon steel exhibited marginally higher cracking tendency w.r.t. number of cracks, total crack length and maximum crack length. Both steels however, exhibited nearly similar threshold strain for cracking (~1.5%). Compared to Cr-Mo steel, silicon and maraging steels exhibited greater cracking tendency. The order of cracking tendency is observed to be silicon steel > maraging steel > Cr-Mo steel. A comparison of micrographs of Varestraint samples of these steels suggests that Cr-Mo steel contains only micro cracks and does not show extensive cracking w.r.t. maximum crack length and total crack length.

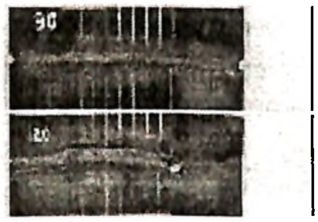

Fig. 4 : Results of Houldcroft testing exhibiting no cracks in the slotted region

The lower cracking tendency of Cr-Mo steel can be thought to be

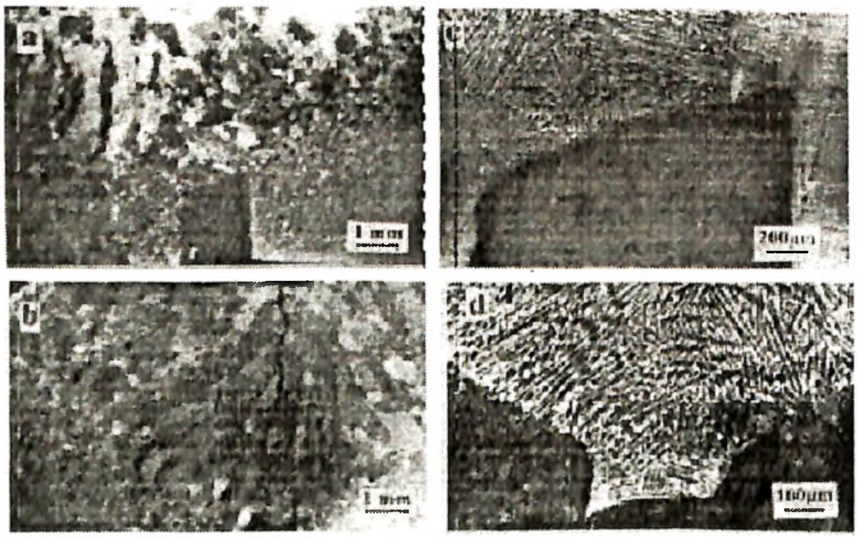

Fig. 3 : Effect of filler metal composition and condition on cold cracking tendency
(a) and (b) Silicon steel filler in the as-received condition
(c) Silicon steel filler in the backed condition
(d) Maraging steel filler wire (W_2) in the as-received condition

Table IV : Varestraint test data on Cr-Mo steel AISI (4130 steel)								
Strain (%)	**No of Cracks**		**Total Crack length (mm)**		**Maximum crack length (mm)**		**Remarks**	
	CC	**PC**	**CC**	**PC**	**CC**	**PC**	**CC**	**PC**
0.236	0	0	0	0	0	0	No cracks	No cracks
0.472	0	0	0	0	0	0	No cracks	No cracks
0.945	0	0	0	0	0	0	No cracks	No cracks
1.89	3	9	0.0365	0.426	0.0125	0.082	Weld microcracks	Weld micro-cracks
3.75	6	10	0.0495	0.492	0.011	0.092	-do-	-do-

CC - Continuous current GTA weld; PC - Pulsed current GTA weld

due to its low alloy content. This steel contains very low Mo and Si and is free from Ni. The intermediate cracking tendency of maraging steel can be attributed to absence of silicon in the steel, and extra low carbon content in the steel. Silicon steel on the other hand exhibited maximum cracking tendency among these steels due to the presence of high silicon as well as high carbon in this steel. The order of grading of these steels with reference to hot cracking is based on the segregation tendency of different alloying elements [6] into the interdendritic regions (Table VI). The order of segregation of the elements is S>P>Si. High carbon and high Ni in silicon steel could promote solidification in austenite mode and therefore would result in more cracking tendency similar to the high carbon effect in quenched and

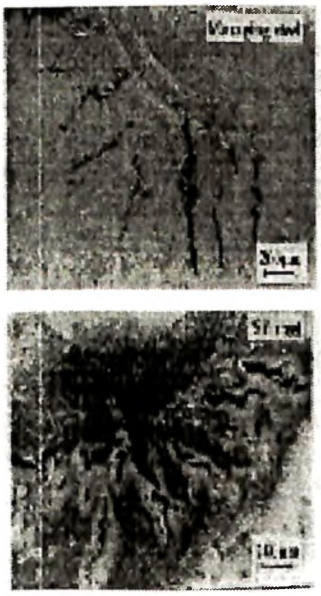

Fig. 5 : Results of Varestraint test at a strain of 3.13% for maraging steel and 2.5% for Si steel

Table V : Varestraint test data on silicon and maraging steels				
Alloy	**Strain (%)**	**No. of cracks**	**Total crack length (mm)**	**Max. crack length (mm)**
Silicon Steel	2.84	12	5	1
	1.42	5	3	1
	0.71	–	–	–
	0.35	–	–	–
	0.18	–	–	–
Maraging Steel	3.13	11	4	0.6
	1.56	5	1.8	0.5
	0.78	–	–	–
	0.39	–	–	–
	0.2	–	–	–

Table VI : Interdendritic segregation of elements in steel											
Element	**S**	**P**	**O**	**C**	**Si**	**MO**	**Ni**	**Mn**	**V**	**Al**	**Cr**
Segregation Coefficient	0.95	0.93	0.9	0.87	0.34	0.3	0.2	0.16	0.1	0.08	0.05

tempered steels [4]. The solidification cracking tendency of 18 Ni maraging steel can be due to liquation effects [16]. The segregation indexes for these steels are presented in Table VII. From this data maraging steel should have been more prone to cracking than silicon steel contrary to the observed trends. This suggests that segregation indexes can not be directly related to hot cracking tendency.

CONCLUSIONS

- Cr-Mo, ultra-high strength silicon steel and 18Ni maraging steel have been studied for their solidification cracking tendencies.
- The cracking tendencies of the steels is in the order silicon steel > maraging steel > Cr-Mo steel.
- The higher cracking tendency of silicon steel is thought to be due to its high silicon and high carbon content and the least cracking tendency of Cr-Mo steel is due to low alloy content of the steel.
- Tekken 'Y' groove test is observed to be suitable for evaluating hot cracking.
- Houldcroft cracking test is not an effective test as the self-restraint is not sufficient to enable grading of the materials for their cracking tendency.

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Table VII : Relative cracking tendency of the steels based on interdendritic segregation of elements

Alloy	Segregation index
Cr-Mo steel	0.64
Silicon steel	2.0
Maraging steel	5.2

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